A standard approach to baseflow separation using the Lyne and Hollick filter

Article *in* Australasian Journal of Water Resources · January 2013

DOI: 10.7158/W12-028.2013.17.1

4 authors, including:

Tony Ladson
University of Melbourne

Rory Nathan
University of Melbourne

A standard approach to baseflow separation using the Lyne and Hollick filter*

AR Ladson†
Department of Civil Engineering, Monash University, Melbourne, Victoria

R Brown, B Neal and R Nathan
Sinclair Knight Merz, Melbourne, Victoria

ABSTRACT: *The digital filtering approach to baseflow separation suggested by Lyne & Hollick (1979) has been widely used and is available in a number of computer packages. However, details of the approach used by different authors vary and so do the results. This means baseflow volumes and indices reported by different authors, and at different times, are difficult to compare. We propose a standard method for baseflow separation using the Lyne and Hollick digital filter. This includes reflecting the flow series at the start and end of the record to reduce "warm up" effects and the adoption of specific starting values for each filter pass.*

KEYWORDS: Baseflow separation; digital filter; Lyne and Hollick; baseflow index.

REFERENCE: Ladson, A. R., Brown, R., Neal, B. & Nathan, R. 2013, "A standard approach to baseflow separation using the Lyne and Hollick filter", *Australian Journal of Water Resources*, Vol. 17, No. 1, pp. 25-34, http://dx.doi.org/10.7158/W12-028.2013.17.1.

1 INTRODUCTION

Separating the baseflow and quickflow components of hydrographs is a common undertaking in hydrology and is used as part of rainfall runoff modelling (Jakeman & Hornberger, 1993), contaminant generation modelling (Merritt et al, 2003), assessments of groundwater recharge and discharge (Arnold et al, 2000), and flood hydrograph estimation (Graszkiewicz et al, 2011). There is a wide range of approaches that have been developed to separate baseflow from quickflow using measured streamflow data (Lyne & Hollick, 1979; Boughton, 1988; Nathan & McMahon, 1990a; Chapman, 1999; Brodie & Hostetler, 2005). It is generally acknowledged that these numerical techniques are not closely related to the underlying physical processes that lead to rapid and delayed responses in streamflow but they offer a way forward for hydrologic practice if they can provide objective and repeatable results.

* Paper W12-028 submitted 18/11/12; accepted for publication after review and revision 11/06/13.

† Corresponding author Dr Tony Ladson can be contacted at tony.ladson@moroka.com.au.

1.1 The Lyne and Hollick filter

Lyne & Hollick (1979) proposed a recursive digital filter for baseflow separation. Although recognised as lacking a physical basis (Chapman, 1991; 1999) the technique is easy to automate, objective and repeatable (Nathan & McMahon, 1991). This makes it particularly useful for comparative hydrology and for regionalisation as it can be used to characterise differences between catchments in a consistent manner. The limitation of the digital filtering approach is that the derived series do not reflect any underlying physical processes in shape, timing or quantum so it is not possible to make quantitative inferences.

The basic filter equations are:

$$q_f(i) = \begin{cases} \alpha q_f(i-1) + \dfrac{(1+\alpha)}{2}\left[q(i) - q(i-1)\right] & \text{for } q_f(i) > 0 \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

$$q_b(i) = q(i) - q_f(i) \tag{2}$$

where $q_f(i)$ is the quickflow response at the i^{th} sampling instant; $q(i)$ is the original streamflow at the i^{th} sampling instant; $q_b(i)$ is the baseflow at the i^{th} sampling instant; and α is the filter parameter that enables the shape of the separation to be altered.

The filter is generally run multiple times through a dataset, for example, for daily data three passes are commonly used, forward, backward and forward. The baseflow index (BFI) is the ratio of the baseflow volume (calculated from q_b) to the volume of streamflow (q) over a specified period.

The Lyne and Hollick approach has been widely used. Baseflow indices based on the Lyne and Hollick filter are presented for 117 streams in 28 river basins in the "Low flow atlas for Victorian streams" (Nathan & Weinmann, 1993). Additional Victorian streams were analysed using the same approach by Lacey (1993) and Lacey & Grayson (1998). Similar methods were also applied to 186 catchments in Victoria and NSW by Nathan & McMahon (1992). Unregulated streams have been analysed in the Murray-Darling Basin: 178 by Neal et al (2004) and 141 by CSIRO & SKM (2010). The approach forms the basis of *Australian Rainfall and Runoff* Revision Project 7, which relates to the use baseflow in catchment simulation for flood estimation (Murphy et al, 2009; 2011; Brown et al, 2011; Graszkewicz et al, 2011). International applications include those by Mugo & Sharma (1999) and Tan et al (2009a; 2009b). The Lyne and Hollick filter is presented as baseflow separation method 3 in Grayson et al (1996).

1.2 The need for a standard approach

Although the basic equation is clear, the specific application of the approach varies. We tested several different software packages all claiming to use the Lyne and Hollick filter but there was substantial variation in the estimated BFI (table 1). There are also different approaches used in Hydstra and IQQM (Hydstra, 2006; Simons et al, 1996). This means that comparison of baseflow indices between studies and over time are difficult and this reduces confidence in the approach. We suggest the Lyne and Hollick filter is still useful but a standard approach to its application is required.

2 STANDARD APPROACH

We propose a standard approach to the use of the Lyne and Hollick filter. This involves:

- reflecting the flow at the start and end of the flow series to address "warm up" issues
- specifying the initial values for each pass
- recommending a number of passes when using daily and hourly data
- specifying a procedure to use when flow data contain missing values
- considering available literature and any supporting data to make an informed decision regarding a suitable parameter value.

In the following, flow is considered as a vector of n values, $q_1, ..., q_n$. In general the units of flow are not important as the BFI is a ratio.

2.1 Reflecting data at the start and end of the flow time series

Application of equation (1) results in issues of "warm up" and "cool down" as the recursive filter is moved backward and forward through the data set. We propose that 30 values of flow be reflected at the start and end of the time series. The input flow series is padded as follows:

$$q_{padded} = q_{31}, q_{30}, ..., q_2, q_1, q_2, ..., q_n, q_{n-1}, ..., q_{n-30}$$

The 30 values are retained during calculations and then discarded before the BFI is calculated.

We tested different amounts of reflection for datasets of different sizes and with various α (filter) parameters. In general: (i) as α increases, the "warm up" effects become larger so reflection becomes more important; and (ii) as the length of the data set increases, the influence of reflection decreases. Once the amount of data is approximately 300 days, the influence of reflection on BFI is negligible. For smaller datasets the amount of reflection does have an influence on BFI and this depends on the α parameter. An example for a small dataset (67 days)

Table 1: Baseflow indices calculated by different programs that implement the Lyne and Hollick approach in various different configurations for sample data set provided in table 3 ($\alpha = 0.925$).

Program	BFI	Reference
BFIP	0.23	Nathan & McMahon (1990b)
Aquapak (1st edition)	0.31	Gordon et al (1994)
River Analysis Package (RAP)	0.23	Marsh (2003)
Aquapak (2nd edition) (SKM, 2012a)	0.39	Gordon et al (2004)
BaseJumper (SKM, 2012b)	0.39	Murphy et al (2008)
BaseflowSeparation	0.22	Fuka et al (2012); R Core Team (2013)
This paper	0.39	

from the Bass River at Lock is shown in figure 1. This dataset is discussed later in the paper.

The figure shows that BFI tends to asymptote to a value which is determined by α as the amount of reflection increases. For smaller values of α the asymptote is reached at smaller amounts of reflection. BFI becomes less sensitive to changes in the amount of reflection as the amount of reflection increases, ie. all the curves in figure 1 flatten as we move to the right.

Ideally it would be best to choose the amount of reflection such that: (i) BFI is near its asymptote value; and (ii) small changes in the amount of reflection have little influence on the value of BFI. This occurs at the right-hand end of figure 1. However insisting on large amounts of reflection would limit the smallest data set that could be analysed (the data set must be longer than the amount of reflection). This may be important when considering data with missing values, as discussed below. As a compromise, we choose to reflect 30 days of values which we found to provide a realistic baseflow response for the start and end of the actual flow data.

2.2 Initial values for each pass

The filter (equation (1)) requires starting values for each pass. It is recommended that these are specified as follows. For the first pass, the starting value of quickflow is set equal to the initial value of streamflow for the padded data set, ie. q_{31} if 30 values are reflected. For the second pass, which is backward, calculations start with the final element q_{n-30}. The initial value for quickflow is set to final value of q_b from the first pass and the filter is applied using the q_b first pass time series as input. For the third pass, the initial value of quickflow is set to the first value of q_b from the second pass and the filter is applied using the calculated time series of q_b from the second pass. The procedure is illustrated later in this paper by a worked example. If more than three passes are required then initial values are selected in the same way, eg. the initial value of q_f for the 4th pass, which would be backward, would be set as the final value of q_b from the 3rd pass, and so on.

2.3 Number of passes

The number of passes that are appropriate to separate baseflow depends on the time step of the flow values. For daily data, it has been common to use three passes and our recommendation is that this be continued. Passes should be in order, forward, backward, forward. For hourly data, extensive testing as part of *Australian Rainfall and Runoff* Project 7 (Murphy et al, 2009; Graszkiewicz et al, 2011) suggests that nine passes are appropriate, alternating forward then backward in a similar manner as for daily flow data. The number of passes has also been used as a calibration parameter in some studies (eg. Hill et al, 2013) with the objective being to match the appearance of baseflow derived from manual methods.

2.4 Missing data

Missing flow data presents a number of challenges for estimating baseflow. Coarse screening of the period of available raw data should be undertaken in the first instance to identify a suitable period of analysis for the given application of the data, particularly where there are large intervals of missing data between periods of available data. After undertaking this coarse screening, missing data may still be present over the desired period of analysis. In some cases it may be possible to infill flow data

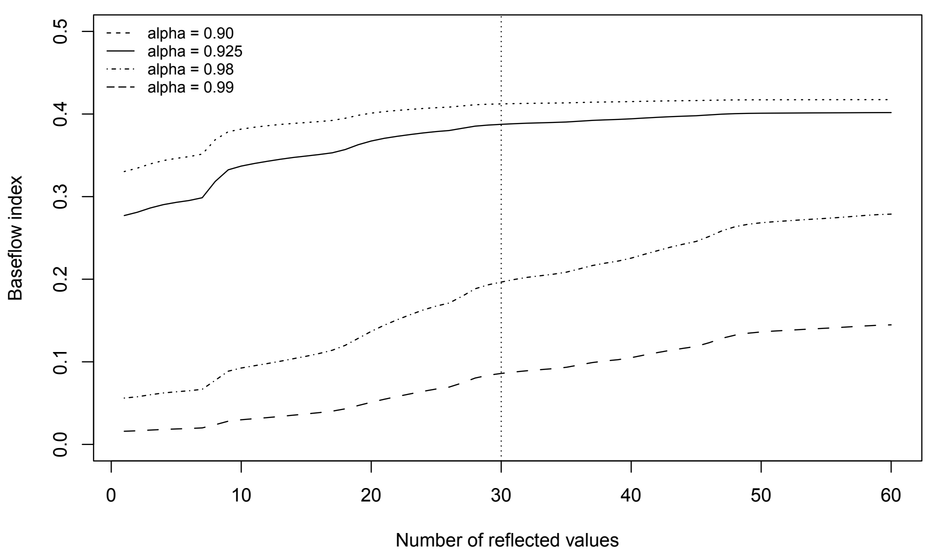

Figure 1: Influence of the amount of reflection and α parameter on calculated BFI for the Bass River at Lock.

prior to estimation of baseflow. If that is not possible then our suggested approach for daily data is as follows. Flow data should be divided into segments of non-missing values. The baseflow is estimated using the procedure outlined above, ie. data should be reflected at each end of each segment. When calculating baseflow statistics, data should only be used from time steps in which raw data were available. For example, the adopted BFI is the sum of baseflow divided by the sum of total flow over the period of available raw data segments. Where flow data has been infilled prior to baseflow separation, it may be appropriate to only use separated baseflow on days where raw data was available to calculate baseflow statistics such as the BFI.

2.5 Selection of the α parameter

The parameter value applied in the filter will influence the nature of the attenuation of the streamflow hydrograph. Historically, a parameter value of 0.925 has been applied as recommended by Nathan & McMahon (1990a). They compared the results of baseflow separation using three parameter values 0.9, 0.925 and 0.95 against two other methods, manual separation and the smoothed minima method (Institute of Hydrology, 1980). Nathan & McMahon (1990a) found that satisfactory results were provided by all three values but recommended a value of 0.925 which gave similar results to manual baseflow separation for 122 catchments in NSW and Victoria ranging in area from 4.2 to 210 km^2. An α value of 0.925 has been widely used and was adopted for *Australian Rainfall and Runoff* Project 6 (Hill et al, 2013) and Project 7 (Murphy et al, 2011).

In recent field studies in nine catchments, BFI values were estimated using chemical tracers (CSIRO & SKM, 2012) (table 2). These estimates were then compared to values of the BFI calculated using the Lyne and Hollick filter with two different α values, 0.925 and 0.98. Results, based on the analysis in (CSIRO & SKM, 2012) are shown in figure 2. These results include an assessment of the uncertainty in the chemical tracer estimates. An α value of 0.98 produced a better match between the two estimates albeit with large scatter. This α value (0.98) was adopted in a baseflow assessment of 141 streams in the Murray-Darling Basin (CSIRO & SKM, 2010). The baseflow estimated using the Lyne and Hollick filter is often taken to represent, at least approximately, the actual baseflow volume in a stream so "calibration" of the α parameter to measurements of baseflow seems reasonable even though the Lyne and Hollick approach is not physically based (Li et al, 2013).

Wherever possible, the selection of the filter parameter value should be informed by field studies using techniques such as chemical tracers and reach water balances. In all cases, the value of the α parameter should be reported along with the results of baseflow separation.

There remains uncertainty in the selection of an appropriate α parameter. If a likely range of α values can be determined then the value of BFI and its uncertainty can be quantified as we show in section 3.

Table 2: Comparison of BFI at nine sites. Baseflow calculated using α parameter values of 0.925, 0.98 and measured using a chemical tracer (SKM & CSIRO, 2012).

Catchment	Nearest gauging station	Latitude, longitude	Catchment area (km^2)	BFI (%)		
				α = 0.925	α = 0.98	Tracer
Barron	Barron River at Picnic crossing (110003)	17.25911, 145.53858	228	63	41	17
Belubula	Belubula River at the Needles (412056)	33.575, 148.842	1610	39	27	NA
Cattle	Cattle Creek at Gargett (125004)	21.17806, 148.74417	326	48	49	27
Cockburn	Cockburn River at Kootingal (419099)	31.062, 151.125	907	36	29	27
Elliot	Elliot River at Dr Mays Crossing (137003)	24.9740, 152.4200	270	66	57	48
Logan	Logan River at Round Mountain (145008)	28.07250, 152.92528	1262	50	44	16
Nambucca	Nambucca River u/s Bowraville (205015)	30.624, 152.843	431	54	54	39
Ourimbah	Ourimbah Ck u/s Weir (211013)	33.34, 151.34	83	46	42	42
Tarcutta	Tarcutta Creek at Old Borambola (410047)	35.15, 147.66	1660	57	32	34

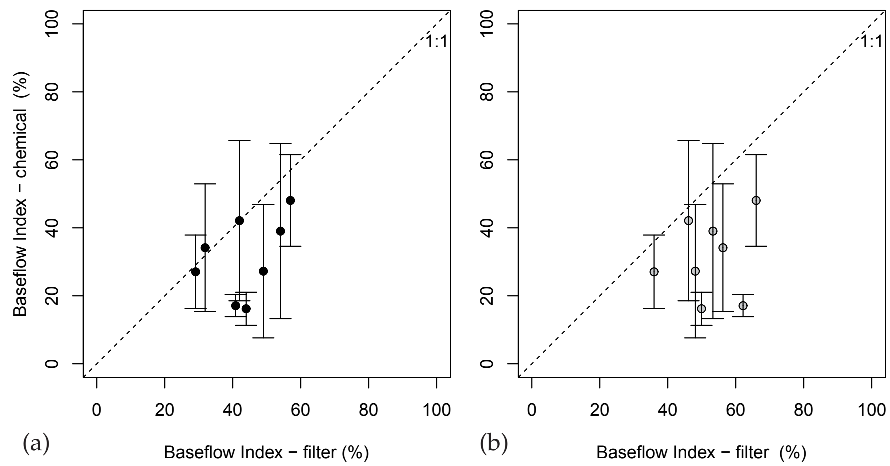

Figure 2: Comparison of BFI values at nine sites. Measured values using chemical tracers were more closely matched using an α value of (a) 0.98, compared with a value of (b) 0.925 (SKM & CSIRO, 2012). Error bars show ±1 standard error.

Table 3: Flow data (ML/d), Bass River at Loch, 30 June and 4 September 1974 (Grayson et al, 1996). Baseflow calculations are explained in the text.

Time index (days)	Flow	Baseflow	Time index (days)	Flow	Baseflow	Time index (days)	Flow	Baseflow
1	5	5	23	260	37.3	45	153	47.6
2	7	7	24	245	38.1	46	247	47.7
3	108	22.1	25	256	38.9	47	703	47.3
4	117	23.2	26	141	39.6	48	498	44.8
5	57	24.1	27	119	40.3	49	286	42.1
6	36	24.6	28	934	41.0	50	163	39.4
7	26	24.7	29	382	41.7	51	124	37.3
8	95	25.3	30	158	42.3	52	85	35.9
9	1169	26.4	31	96	42.8	53	94	34.8
10	308	27.5	32	122	43.4	54	81	33.8
11	144	28.5	33	103	43.9	55	62	33.0
12	89	29.5	34	83	44.3	56	47	32.6
13	62	30.4	35	67	44.8	57	37	32.4
14	48	30.9	36	148	45.2	58	30	30
15	40	31.1	37	366	45.6	59	26	26
16	35	31.2	38	161	46.0	60	24	24
17	73	31.7	39	119	46.3	61	24	24
18	82	32.6	40	82	46.6	62	22	22
19	342	33.6	41	330	46.9	63	21	21
20	393	34.6	42	294	47.2	64	20	20
21	310	35.5	43	261	47.3	65	19	19
22	275	36.4	44	266	47.5	66	18	18
						67	18	18

3 CASE STUDY

The proposed standard method is applied to a case study for the Bass River at Loch using the same data set discussed by Grayson et al (1996, p. 79). This is based on 67 values of flow (ML/d) between 30 June and 4 September 1974 (table 3).

Padding the flows to reflect the values at each end of the series results in the following values q_{31}, ..., q_2,

$q_1, q_2, \ldots, q_{67}, q_{66}, \ldots, q_{37}$ (figure 3). Sample calculations for the first two rows of the padded flow series are shown in table 4. An α value of 0.98 was adopted. These sample calculations are indicative of the procedures that would be required for all 127 rows, ie. 67 rows with the flow data and 30 additional rows that are padded at each end. For this data set, the total volume of stream flow is 11,616 ML, the total volume of baseflow is 2283 ML so the BFI is 0.20. Baseflow is plotted on figure 3.

3.1 Sensitivity of BFI estimates to α parameter

The sensitivity of BFI results to various values of α parameter can be quantified. The BFI for this example was calculated for a range of α values between zero and 1 (table 5, figure 4). There is a rapid decrease in BFI values once α increases above about 0.94.

If there was only sufficient information to determine a range of likely α values rather than a particular value, then stochastic sampling could be used to quantify the BFI and its uncertainty.

For example, if α was thought to be equally likely to be anywhere in the range 0.9 to 0.98, calculations would proceed as follows:

1. Generate a large number of random α values uniformly distributed in the range 0.9 to 0.98.
2. Calculate BFI for each α.
3. Estimate the median BFI value and for a 90% confidence interval, the 25th and 95th percentile values.

Results for the case study data are shown in table 6 and figure 5. Results show a median value of 0.37 with 95% confidence interval (0.24 to 0.41). The range of the confidence interval can only be reduced if better information can be obtained for the α parameter.

Table 5: BFI for various α values.

α	BFI
0.000	0.67
0.900	0.41
0.925	0.39
0.950	0.34
0.980	0.20
0.987	0.12

Table 4: Sample calculation of base flows for Bass River at Loch (only the first two lines of calculations are shown), α = 0.98.

Time index (days)	Q	First pass (forward)		Second pass (backward)		Third pass (forward)	
		q_f pass 1	q_b pass 1	q_f pass 2	q_b pass 2	q_f pass 3	q_b pass 3
31	96	96[a]	0	–63.31[d]	0[e]	0[g]	0[i]
30	158	155.46[b]	2.54[c]	–62.04	2.54[f]	2.51[h]	0.03[j]

Notes: [a] initial value set to the first flow value; [b] 0.98 × 96 + (158 – 96) × (1 + 0.98)/2 = 155.46; c 158 – 155.46 = 2.54; [d] 0.98 × –62.04 + (0 – 2.54) × (1 + 0.98)/2 = –63.31; [e] q_f pass 2 < 0 so q_b pass 2 = q_b pass 1 = 0; [f] q_f pass 2 < 0 so q_b pass 2 = q_b pass 1 = 2.54; [g] initial value set to base flow from pass 2; [h] 0.98 × 0 + (2.54 – 0) × (1 + 0.98)/2 = 2.51; [i] 0 – 0 = 0; and [j] 2.51 – 2.54 = 0.03.

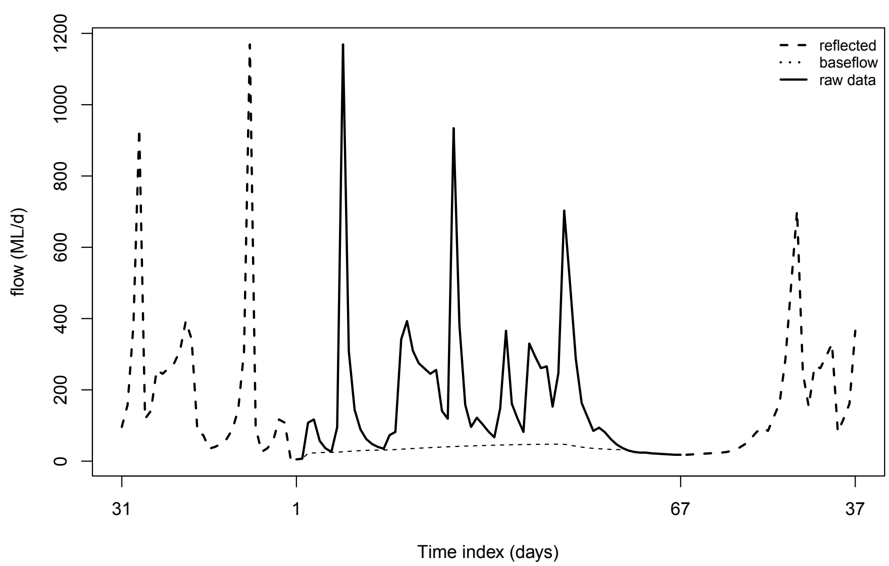

Figure 3: Time series of flows for the Bass River at Loch. Thirty values at either end of the time series have been reflected

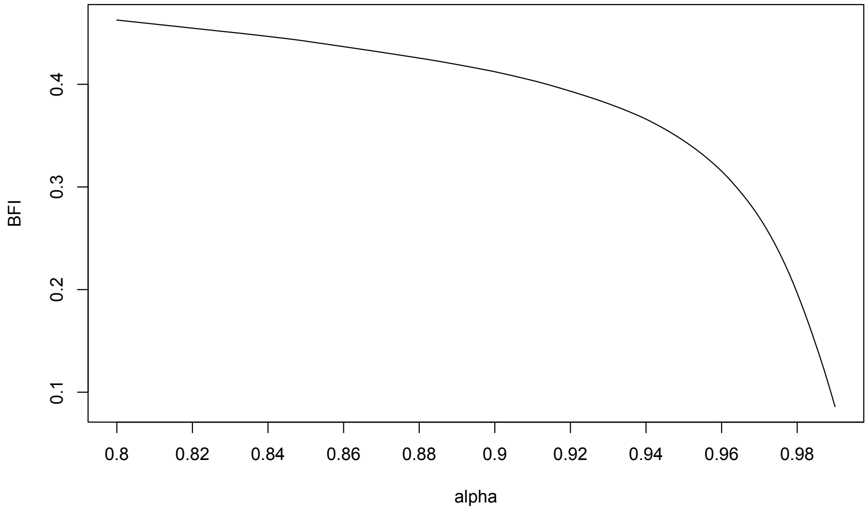

Figure 4: BFI as a function of α for Bass River at Loch.

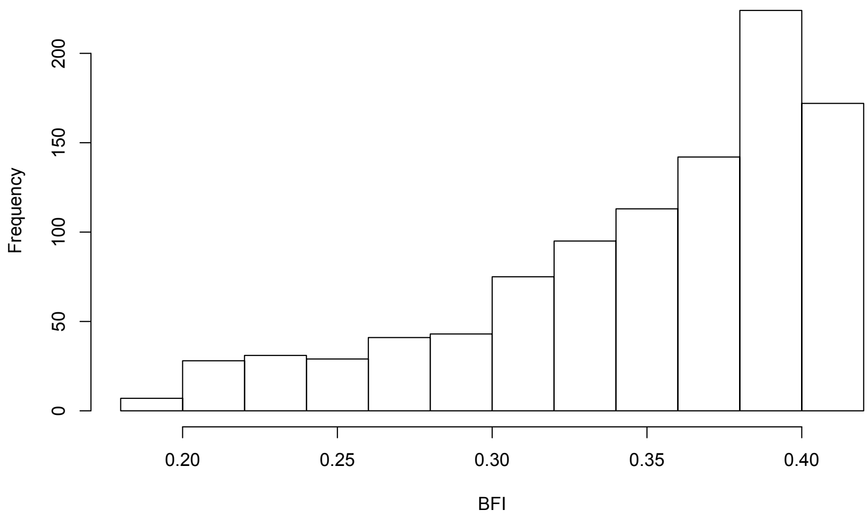

Figure 5: BFI results for 1000 α values in the range 0.90 to 0.98.

Table 6: BFI for 1000 samples of α in the range 0.90 to 0.98.

Parameter	Value
Mean	0.35
Median	0.37
5% confidence limit	0.24
95% confidence limit	0.41

If there is sufficient knowledge of the α parameter to identify a central tendency in its distribution, then the simulation at step 1, above, could be altered to generate samples from any desired distribution.

4 CONCLUSIONS

The use of a standard approach to baseflow separation using the Lyne and Hollick filter provides for comparison between studies and allows practitioners to calculate baseflows in a way that is consistent with the recommendations in *Australian Rainfall and Runoff* Project 7. We have documented a standard approach based on:

1. reflecting data at each end of a flow series
2. specifying initial values to be used for each pass of the filter
3. recommending a standard number of passes that depend on the time step of the flow data
4. specifying when baseflow should be constrained so that it does not exceed the original flow or become less than zero
5. recommending a standard approach to deal with missing data in the flow series.

The selection of an appropriate α value remains an open question. It has been common to use a value of 0.925, however, recent comparisons of modelled and measured baseflow values in the Murray

Darling Basin suggest a value of 0.98 produces more reasonable results. We show how to calculate the uncertainty in the BFI if a range of α parameters can be specified. If possible the α should be calibrated against chemical tracers and reach water balances, and the adopted α value should always be reported. Significant uncertainties in baseflow separations will remain until the links between baseflow and physical factors are better understood and can be taken into account in baseflow separation procedures.

ACKNOWLEDGEMENTS

We would like to acknowledge the assistance of Dwain Dawes who undertook some of the initial work while a student at Monash University. The contributions of two anonymous reviewers are acknowledged with thanks.

REFERENCES

Arnold, J. G., Muttiah, R. S., Srinivasan, R. & Allen, P. M. 2000, "Regional estimation of baseflow and groundwater recharge in the Upper Mississippi River Basin", *Journal of Hydrology*, Vol. 227, pp. 21-40.

Boughton, W. C. 1988, "Partitioning streamflow by computer", *Civil Engineering Transactions*, Vol. CE30, No. 4, pp. 285-291.

Brodie, R. S. & Hostetler, S. 2005, "A review of techniques for analysing baseflow from stream hydrographs", *Where Waters Meet*, Auckland, New Zealand, New Zealand Hydrological Society (NZHS).

Brown, R. E., Graszkiewicz, Z., Hill, P. I., Neal, B. P. & Nathan, R. J. 2011, "Predicting baseflow contributions to design flood events in Australia", *33rd Hydrology and Water Resources Symposium*, Brisbane, 26 June to 1 July, Engineers Australia, pp. 64-73.

Chapman, T. G. 1991, "Comment on 'Evaluation of automated techniques for base flow and recession analysis' by R. J. Nathan and T. A. McMahon", *Water Resources Research*, Vol. 27, No. 7, pp. 1783-1784

Chapman, T. 1999, "A comparison of algorithms for stream flow recession and baseflow separation", *Hydrological Processes*, Vol. 13, pp. 701-714.

CSIRO & SKM, 2010, *Baseflow assessment for the Murray-Darling Basin*, Water for a Healthy Country National Research Flagship, CSIRO, 78 pp.

Fuka, D. R., Walter, M. T., Archibald, J. A., Steenhuis, T. S. & Easton, Z. M. 2012, "EcoHydRology: A community modelling foundation for Eco-Hydrology", R package version 0.4.5, http://CRAN.R-project.org/package=EcoHydRology.

Gordon, N. D., McMahon, T. A. & Finlayson, B. L. 1994, *Stream hydrology: an introduction for ecologists*, 2nd edition, Wiley.

Gordon, N. D., McMahon, T. A., Finlayson, B. L., Gippel, C. J. & Nathan, R. J. 2004, *Stream hydrology: an introduction for ecologists*, 2nd edition, Wiley.

Graszkiewicz, Z., Murphy, R. E., Hill, P. I. & Nathan, R. J. 2011, "Review of techniques for estimating the contribution of baseflow to flood hydrographs", *33rd Hydrology and Water Resources Symposium*, Brisbane, 26 June to 1 July, Engineers Australia, pp. 138-146.

Grayson, R. B., Argent, R. M., Nathan, R. J., McMahon, T. A. & Mein, R. G. 1996, *Hydrological Recipes*, Cooperative Research Centre for Catchment Hydrology, Melbourne.

Hill, P. I., Graszkiewicz, Z., Sih, K. & Rahman, A. 2013, "Loss models for catchment simulation – rural catchments", *Australian Rainfall and Runoff* Revision Project 6, Engineers Australia.

Hydstra 2006, "HYBASE enhancement and bug fix (2006/11/22)" http://hydstra.kisters.com.au/whatsnew906.pdf.

Institute of Hydrology, 1980, "Low Flow Studies", Res. Rep. 1, Wallingford, UK.

Jakeman, A. J. & Hornberger, G. M. 1993, "How much complexity is warranted in a rainfall-runoff model?", *Water Resources Research*, Vol. 29, No. 8, pp. 2637-2649.

Lacey, G. C. 1993, "Relating baseflow to catchment properties: a scaling approach", Report 96/8, Cooperative Research Centre for Catchment Hydrology.

Lacey, G. C. & Grayson, R. B. 1998, "Relating baseflow to catchment properties in south-eastern Australia", *Journal of Hydrology*, Vol. 204, No. 1-4, pp. 231-250.

Li, L., Maier, H. R., Lambert, M. F., Simmons, C. T. & Partingon, D. 2013, "Framwork for assessing the improving the performance of recursive digital filters for baseflow estimation with application to the Lyne and Hollick filter", *Environmental Modelling & Software*, Vol. 41, pp. 163-175.

Lyne, V. & Hollick, M. 1979, "Stochastic time-variable rainfall-runoff modelling", *Proceedings of the Hydrology and Water Resources Symposium*, Perth, 10-12 September, Institution of Engineers National Conference Publication, No. 79/10, pp. 89-92.

Marsh, N. 2003, *RAP: River Analysis Package*, Version 1.1, www.toolkit.net.au/rap.

Merritt, W. S., Letcher, R. A. & Jakeman, A. J. 2003, "A review of erosion and sediment transport models", *Environmental Modelling & Software*, Vol. 18, pp. 761-799, doi:10.1016/S1364-8152(03)00078-1.

Mugo, J. M. & Sharma, T. C. 1999, "Application of a conceptual method for separating runoff components in daily hydrographs in Kimakia Forest Catchments, Kenya", *Hydrologic Processes*, Vol. 13, No. 17, pp. 2931-2939.

Murphy, R., Neal, B., Morden, R., Nathan, R. N. & Evans, R. 2008, "BaseJumper – tool for analysing time trends in baseflow", Water Down Under, Adelaide, Engineers Australia.

Murphy, R., Graszkiewicz, Z., Hill, P., Neal, B., Nathan, R. & Ladson, T. 2009, *Australian Rainfall and Runoff Revision Project 7: Baseflow for Catchment Simulation*, Stage 1 report, P7/S1/004, Engineers Australia, www.arr.org.au/Website_links/ARR_Project_7_Stage1_report_Final.pdf.

Murphy, R., Graszkiewicz, Z., Hill, P., Neal, B., Nathan, R. & Ladson, T. 2011, *Australian Rainfall and Runoff Revision Project 7: Baseflow for Catchment Simulation*, Stage 2 report, P7/S2/017, Engineers Australia, www.arr.org.au/Website_links/ARR_P7_Stage2_Final_Report.pdf.

Nathan, R. J. & McMahon, T. A. 1990a, "Evaluation of automated techniques for base flow and recession analysis", *Water Resources Research*, Vol. 26, pp. 1465-1473.

Nathan, R. J. & McMahon, T. A. 1990b, "The estimation of low flow characteristics and yield from small ungagued rural catchments", AWRAC Research Project, No. 85/105.

Nathan, R. J. & McMahon, T. A. 1991, "Reply (to Chapman, 1991)", *Water Resources Research*, Vol. 27, No. 7, pp. 1785-1786.

Nathan, R. J. & McMahon, T. A. 1992, "Estimating low flow characteristics in ungauged catchments", *Water Resources Management*, Vol. 6, pp. 85-100.

Nathan, R. J. & Weinmann, P. E. 1993, "Low flow atlas for Victorian streams", Department of Conservation and Natural Resources, Victoria.

Neal, B. P., Nathan, R. J. & Evans, R. 2004, "Survey of baseflows in unregulated streams of the Murray-Darling Basin", 9th Murray-Darling Basin Groundwater Workshop, New Zealand Society of Soil Science (NZSSS).

R Core Team, 2013, *R: A language and environment for statistical computing*, R Foundation for Statistical Computing, Vienna, Austria, ISBN 3-900051-07-0, www.R-project.org.

Simons, M., Podger, G. & Cooke, R. 1996, "IQQM – A hydrologic modelling tool for water resources and salinity management", *Environmental Software*, Vol. 11, pp. 185-192.

Sinclair Knight Merz (SKM), 2012a, "AQUAPAK", www.globalskm.com/aquapak.

Sinclair Knight Merz (SKM), 2012b, "BaseJumper",www.globalskm.com/basejumper.

SKM & CSIRO, 2012, "Methods for estimating groundwater discharge to streams – summary of field trials. National Water Commission", www.environment.gov.au/water/policy-programs/water-smart/projects/pubs/methods-estimating-groundwater-discharge-streams.pdf.

Tan, S. B. K., Lo, E. Y., Shuy, E. B., Chua, L. H. C. & Lim, W. H. 2009a, "Generation of total runoff hydrographs using a method derived from a digital filter algorithm", *Journal of Hydrologic Engineering*, Vol. 14, No. 1, pp. 101-106.

Tan, S. B. K., Lo, E. Y., Shuy, E. B., Chua, L. H. C. & Lim, W. H. 2009b, "Hydrograph separation and development of empirical relationships using single parameter digital filters", *Journal of Hydrologic Engineering*, Vol. 14, No. 3, pp. 271-279.

ANTHONY LADSON

Tony Ladson has more than 25 years' experience in hydrology and river management and has worked on projects throughout Australia, the US and Taiwan. He has a PhD from the University of Melbourne, a Master of Science from the University of Minnesota and also studied at Uppsala University in Sweden. He is a director of Moroka Pty Ltd, an honorary fellow at the University of Melbourne and a teaching fellow in the Department of Civil Engineering at Monash University, where he delivers post-graduate courses on water resources, urban drainage infrastructure and flood management. One of Tony's main interests is the application of hydrologic principles to improve the environmental condition of Australia's rivers. Tony has more than 90 refereed publications and has completed a book on Australian hydrology for Oxford University Press.

RACHEL BROWN

Rachel Brown is a water resources engineer with SKM, and has qualifications in environmental engineering, botany and water resource management. She has worked on a Natural Heritage Trust study into groundwater and surface water condition change, which involved hydrologic analysis of data to identify user-friendly approaches to baseflow separation from streamflow data, trend analysis to understand baseflow contribution to streamflow, and the development of a tool (Basejumper) to support water resource managers in understanding changes in baseflow trends. Rachel was also involved in a project for the update of the *Australian Rainfall and Runoff* guidelines that developed a simple approach to estimate baseflow contribution to design flood events based on readily available catchment characteristics. Rachel is also actively involved in the water engineering community and is currently Chair of the Victorian Water Engineering Branch of Engineers Australia.

BRAD NEAL

Brad Neal is SKM's practice leader for water resource planning and has 18 years' experience in hydrology and water resource management. In the area of groundwater and surface water interaction, Brad has provided technical input and review to the development of guidelines for groundwater trend analysis for coal seam gas activities, the development of the Basejumper software for baseflow separation and trend analysis, the contribution of baseflow to design flood peaks and the estimation of baseflow indices in unregulated rivers across the whole of Victoria, the Murray-Darling Basin and tropical northern Australia.

RORY NATHAN

Dr Rory Nathan is the Practice Leader for Hydrology with SKM. He holds degrees in different aspects of engineering hydrology from the universities of Melbourne and London, and has around 30 years' experience in academic and consulting positions. Rory's technical interests are in the modelling of hydrological processes, environmental hydrology, and the analysis and simulation of extreme events.